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Use of the Vertical Motion Simulator in Support of the American Airlines Flight 587 Accident Investigation

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As part of the investigation of the accident involving American Airlines Flight 587, the National Transportation Safety Board (NTSB), in cooperation with NASA Ames Research Center, proposed to conduct observations and tests using the Vertical Motion Simulator (VMS). The investigation was divided into two phases. Phase I consisted of evaluating the accelerations experienced during the accident event by back-driving the cockpit controls, displays, out-the-window scene, cockpit communications, and motion of the aircraft as recorded and derived from the aircraft's flight data recorder (FDR) and cockpit voice recorder (CVR). Phase II consisted of evaluating the effects of flight control characteristics and accelerations similar to those experienced during the accident event on pilot perception and performance using a tracking task. The tracking task consisted of pilots following an on-screen target with various flight control configurations, with both motion off and motion being back-driven using derived acceleration data from the FDR. This paper describes the work provided by the VMS in support of the investigation and does not include any conclusions drawn from the study.

I. Introduction

ON November 12, 2001, American Airlines Flight 587, an Airbus A300-600, was destroyed when it crashed into a residential area of Belle Harbor, New York, shortly after takeoff from John F. Kennedy International Airport (JFK). The aircraft crashed after its rudder and vertical stabilizer separated from the airframe in flight. From information provided by the National Transportation Safety Board (NTSB), flight 587 experienced two instances of turbulence consistent with encountering the wake vortices from a Boeing 747 that departed JFK ahead of the Airbus A300-600 before the separation of rudder and vertical stabilizer. The two airplanes were separated by about five miles and ninety seconds at the time of the vortex encounters. During and shortly after the second wake encounter, the flight data recorder (FDR) on American 587 recorded several large rudder movements to full or nearly full available rudder deflection in both directions. Most transport airplanes are equipped with rudder limiter systems that limit rudder deflection at higher airspeeds and that prevent single rudder inputs from causing structural overload. However, pilots may not be aware that full or nearly full rudder deflection in one direction followed by a similar deflection in the other direction may result in structural loads that exceed the structural capabilities of the aircraft even at speeds below the design maneuvering speed.[1]

Among the potential causes being examined for the accident were rudder system malfunction and flight crew actions. The NTSB, represented by the Human Performance Group and in cooperation with the VMS at NASA Ames Research Center, proposed a two-phase approach to the investigation. The goals of Phase I were to evaluate the accelerations and angular motions and to evaluate cockpit displays, visual cues, and flight control motions similar to those experienced during the accident. This phase consisted of back-driving the cockpit controls, displays, out-the-window (OTW) scenes, cockpit communications, and motion of the aircraft as derived from the FDR and the cockpit voice recorder (CVR). The goal of Phase II was to evaluate the effects of flight control characteristics

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and accelerations similar to those experienced during the accident on pilot perception and performance using a tracking task. Phase I and Phase II were conducted during August 2002. The remainder of this paper describes the work provided by the VMS in support of Phase I and Phase II as described above.

II. Vertical Motion Simulator

A. Body Force Cueing System

The VMS motion system, the world's largest flight simulation motion base, is a six degree-of-freedom (DOF) electromechanical/electrohydraulic servo system (Fig. 1). The motion system consists of two integrated motion generators: an electrically driven system, which provides two translational DOF, and a hydraulically driven system, which provides the remaining translational and three rotational DOF. Displacement, rate, and acceleration limits of the VMS motion system are shown in Table 1.

Table 1. System limits of the VMS motion base.

Axis	Displacement	Velocity	Acceleration
Roll	+/- 18 deg	+/- 40 deg/s	+/- 115 deg/s^2
Pitch	+/- 18 deg	+/- 40 deg/s	+/- 115 deg/s^2
Yaw	+/- 24 deg	+/- 40 deg/s	+/- 115 deg/s^2
Long.	+/- 4 ft	+/- 4 ft/s	+/- 10 ft/s^2
Lat.	+/- 20 ft	+/- 8 ft/s	+/- 16 ft/s^2
Vertical	+/- 30 ft	+/- 16 ft/s	+/- 24 ft/s^2

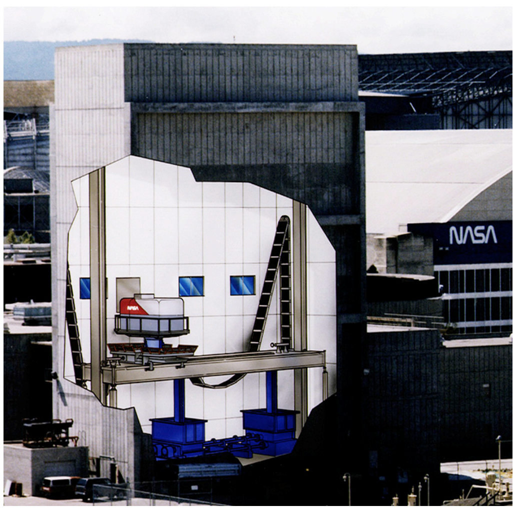


Figure 1. The NASA Ames VMS motion system.

B. Math Models

Phase I required only playback data derived from FDR data. FDR data was used to drive the motion system, the primary flight controls, and the primary flight display (PFD). FDR parameters were sampled at a rate of between 1 and 8 Hz. The VMS systems were backdriven with interpolated data for all parameters sampled at 50 Hz.[2] Phase II also required playback files to drive the amplitude and frequency of the tracking task display symbols. All playback files were hosted on a Compaq Alpha DS-20e 667 MHz processor machine with 1 GB of RAM at a 50 Hz cycle time.

C. Cab Configuration

An interchangeable cab, referred to as T-cab, was used for the simulation. T-cab had a two-seat cockpit configuration (Fig. 2) similar to that of transport type airplanes. Out-the-window scenes were provided by a collimated display system using six monitors with five channels of computer-generated imagery, where the two center windows were duplicated. Cockpit displays were provided with three side-by-side 8-inch monitors for each seat. Flight controls for each seat were provided by a wheel-and-column system and adjustable rudder pedals. A four-throttle lever quadrant between the seats was also provided where levers 1 and 2 were mechanically linked together to indicate lever position from throttle 1 of the FDR data and levers 3 and 4 were mechanically linked together to indicate lever position from throttle 2 of the FDR data.

For Phase I, two backdrive conditions were programmed for the rudder pedal. The first condition corresponded to rudder pedal position based on FDR values. In the second condition, the rudder pedal approximated the variable ratio limiter system to determine what the pedal inputs required to achieve the accident rudder deflections would feel like on such a system compared to the variable stop system actually used on the airplane. Both conditions were backdriven with playback files delivered by the NTSB. For the Phase II study, the VMS control loader characteristics were programmed to emulate the control system characteristics of the A300-600 aircraft. Specifically, the VMS pedal was programmed to evaluate the "variable stop" rudder design of the A300-600 aircraft, in which the forces and displacements needed to command maximum rudder travel varied as a function of airspeed. Table 2 shows a comparison of the pedal force and displacement characteristics between the A300-600 and the VMS for three airspeeds. [3]

Figure 2. T-cab configuration for Phase I and Phase II.

Table 2. Pedal force and displacement characteristics for the A300-600 and the VMS.

	165 kts		240 kts		310 kts	
	Max Pedal Force (lbs)	Max Pedal Travel (in)	Max Pedal Force (lbs)	Max Pedal Travel (in)	Max Pedal Force (lbs)	Max Pedal Travel (in)
A300-600	66.1	4	35.3	1.44	28.6	0.66
VMS	66.1	3.5	40.6	1.48	31.8	0.78

D. Visual and Display Systems

A JFK visual database was developed for the simulation. Among the existing databases at the VMS, two databases included the JFK area: Pease AFB and Atlantic City. After some investigation, it was decided that the Atlantic City database would be modified to represent the JFK area. NTSB researchers also provided JPEG files of aerial pictures of the JFK airport and the surrounding area, which helped to create a more realistic database. The visual database was hosted on an Evans and Sutherland Image Generator (ESIG) 3000, a six-channel product capable of producing 3000 polygons per channel at 60 Hz, with a resolution of 1024 x 768 interlaced.

The simulated cockpit instruments were graphically displayed on two of the three CRT monitors mounted on a panel directly in front of each seat. The center monitor displayed a replica of the A300 primary flight display (PFD) showing altitude, attitude, and airspeed information (Fig. 3). The left monitor showed the replica of the A300 navigation display of heading and track information (Fig. 4). The right monitor displayed video strip charts of input and actual accelerations for the longitudinal, lateral, and vertical axes and the flight control positions. For Phase II operation, only the tracking task visual display was shown on the center monitor (Fig. 5). The instrument display models were developed and implemented on SGI 230 PC's running Redhat OpenLinux and coded with OpenGL.

E. Sound Systems

Due to the sensitive nature of the CVR audio recordings, the actual CVR files were hand delivered, and precautions were taken to protect those sound files, including limiting access to the transmission of the CVR to only those authorized by the NTSB. During selected backdrive runs of Phase I, a synchronized audio file containing the CVR sound was played over the headsets of those participants cleared to listen to the CVR audio segments. The NTSB delivered three sound files for inclusion in the simulation. These sound files were recorded from different sources such as cockpit area microphone, air traffic control transmissions, and intra-cockpit communications. One or all of the files were mixed and played back to the lab and cab headsets. The NTSB also delivered a test sound file with a timestamp for the first message in the file. This allowed for the verification of the time sync of the playback data with the sound. The sound files were hosted on the ASTi Digital Audio Communications System (DACS), based on a Pentium III PC running DOS. File conversion was necessary for hosting on the ASTi system, and when necessary, the files were shortened to obtain the correct timing for synchronization.

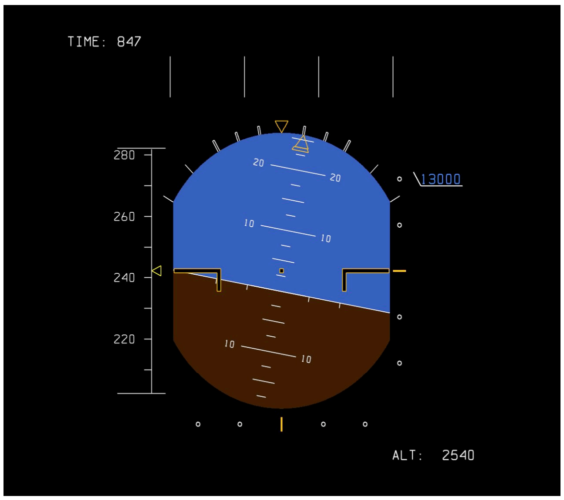


Figure 3. Primary Flight Display.

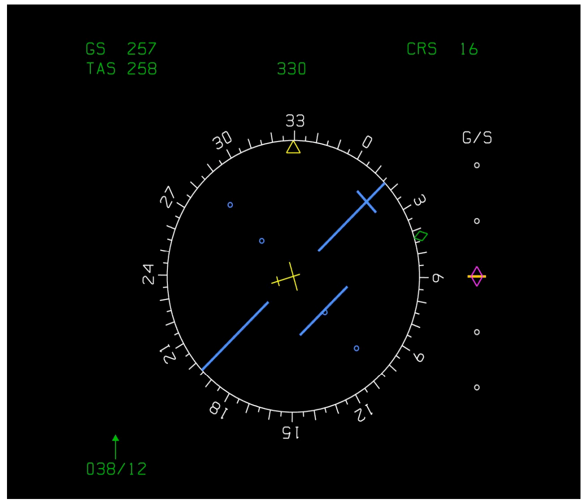


Figure 4. Navigation Display.

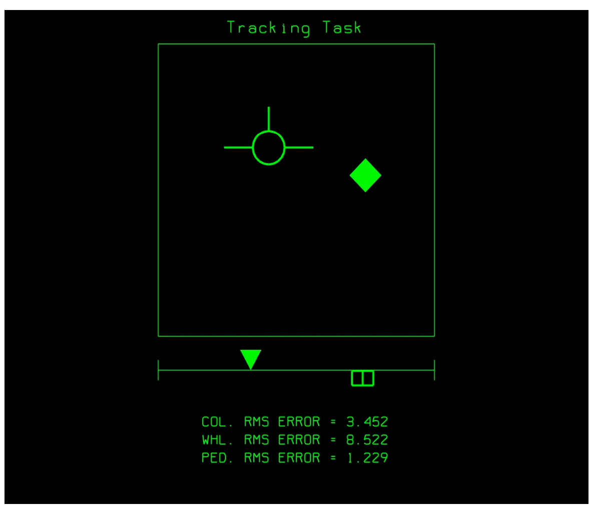


Figure 5. Tracking Task Display. The commanded wheel and column positions are shown by the solid diamond. The actual wheel and column positions are shown by the airplane symbol. The commanded pedal position is indicated by the solid triangle, and the actual pedal position is indicated by the rectangular "bug".

F. Control Room Layout and Data Collection

During operation of the simulation, video information was presented in the control room via a bank of eight flat panel monitors. These monitors presented the center window of the out-the-window scene, the PFD display, the navigation display, a "chase plane" view of the simulated aircraft (Fig. 6), and video strip charts identical to those displayed in the cab. Also displayed was a graphical presentation of the dynamic flight control position information and rudder travel limiter position information (Fig. 7).

For both Phase I and Phase II, real-time data was recorded in binary format at 50 Hz using a variable list provided by the NTSB. The NTSB also requested that the root mean square error of the column, wheel, and pedals be calculated and displayed during the tracking task study to allow for monitoring of the parameters more closely and for providing immediate feedback to the pilots. One video recording was made of an overhead view of the cab and it's occupants. Another video recording was made of a quad display of the video strip chart, the PFD, the flight control display, and the "chase plane" view. Verbal comments made by the group members at the conclusion of each run were also recorded.

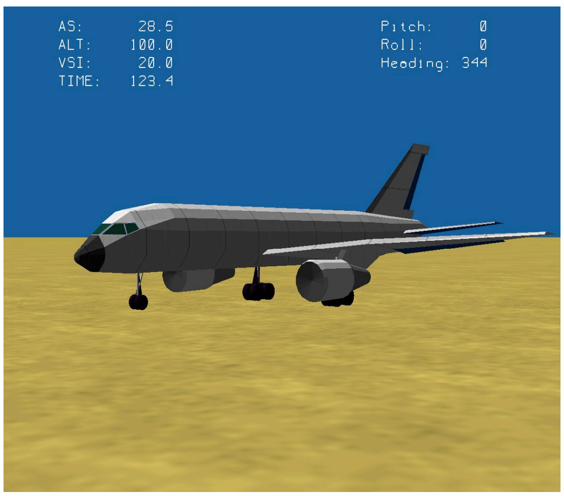


Figure 6. "Chase Plane" View.

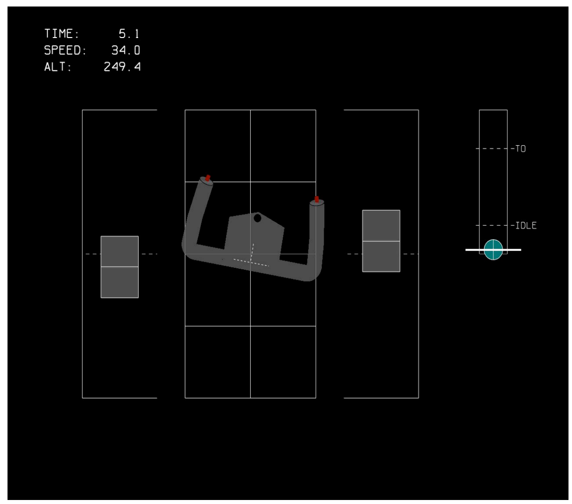


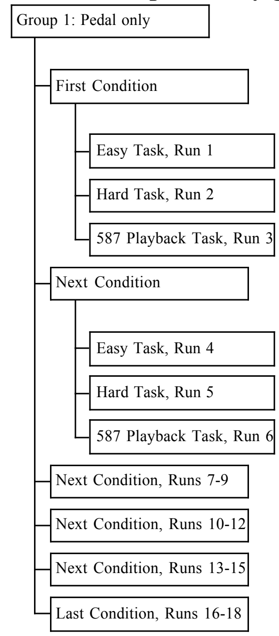
Figure 7. Dynamic Flight Control Position.

III. Phase I & Phase II

During August 2002, the NTSB Human Performance Group conducted tests and observations at the Vertical Motion Simulator for a period of two weeks incorporating the objectives of both Phase I and Phase II. For Phase I, the Human Performance Group experienced the VMS backdrive of the time histories of derived pilot station accelerations computed from the FDR accelerometer data. The primary flight controls, including the rudder pedals, the control wheel and column, and the throttles were also backdriven from interpolated FDR data. The experience included full motion on the VMS with maximum motion envelope, OTW visual scenes of the JFK area, the primary flight display, the navigation display, and video strip charts display presented to the cab occupants. The aural cue system presented the synchronized audio segments from the CVR to authorized personnel in the cab via headsets. In all, the group members experienced four specific setups: 1) full motion and backdrive of flight controls with the pedals driven by FDR data, 2) full motion and backdrive of flight controls with the pedals approximated as a variable ratio limiter system, 3) full motion and no backdrive of flight controls, and 4) no motion and backdrive of flight controls with the pedals driven by FDR data.

For Phase II, the test subjects performed the tracking task. Seven pilots participated in this phase of the study. Four pilots were American Airlines A300-600 line pilots current in the airplane with flight times ranging from 1,331 to 2,501 hours. Two pilots were Human Performance group members and test pilots with type ratings in the A300-600. One pilot was a NASA test pilot not type rated in the airplane.[3] Test subjects were instructed to move the controls to track the commanded control positions, where both the commanded and actual positions were displayed on the center monitor (Fig. 5). During the tracking task, the OTW visual displays were turned off. The test was organized by groups of flight controls that were being driven at any one time. Group 1 was pedal only. Group 2 was pedal and wheel. Group 3 was pedal, wheel, and column. These groups were further organized into six conditions that combined control loader characteristics and motion state. The control loader characteristics were for the three airspeeds discussed previously (Table 2), and the motion state referred to either fixed-base or the VMS recreation of motion from the last sixty seconds of the FDR. During performance of the tracking tasks, the pilot did not have control of the motion system but rather experienced the motion backdrive only. Three different one-minute tracking tasks were performed for each combination of group and condition. The "easy" task was characterized by relatively low frequency and low amplitude oscillations. The "hard" task was characterized by higher frequency and higher amplitude oscillations. The "587" task consisted of tracking the flight control movements from the last sixty seconds of the FDR. For the "easy" and "hard" tracking tasks, the wheel and pedal followed the same path and the column followed a slightly different path. All three tasks were in the form of playback files as delivered by the NTSB. Figure 8 and figure 9 show the pedal only tracking tasks for the "easy" and "hard" tasks. Consequently, each subject performed a total of 54 runs for every combination of group, condition, and task. It should be noted that the groups were always performed in the order of Group 1, Group 2, and Group 3, and the tasks always performed in the order of "easy", "hard", and "587", whereas the conditions were randomized for each subject. Prior to each test session, a pilot went through a short training phase to become familiar with the controls, the task, and the motion. Table 3 shows the test matrix for the pedal only group.

Table 3. Test matrix for pedal only group.



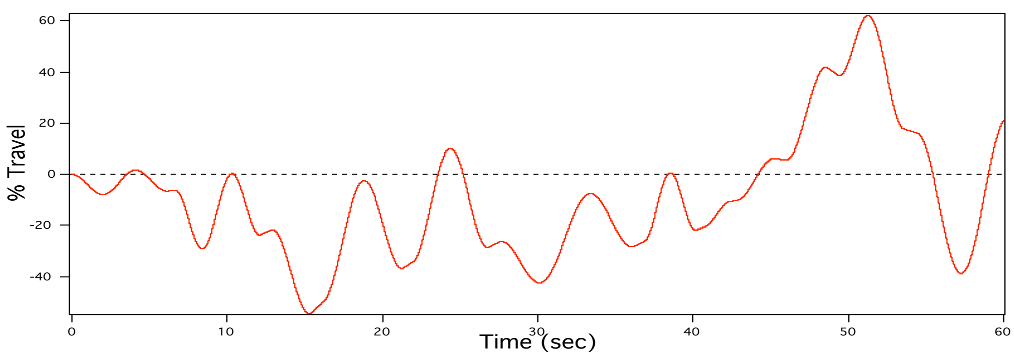


Figure 8. "Easy" tracking task for the pedal.

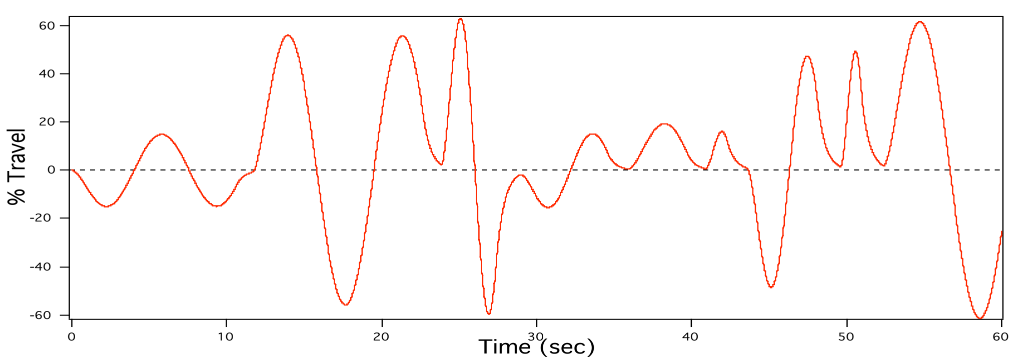


Figure 9. "Hard" tracking task for the pedal.

IV. Conclusion

The VMS provided support to the NTSB Human Performance Group in its accident investigation of American Airlines Flight 587. The resources at the VMS were made available to the NTSB during a two-week period of August 2002 to conduct tests and observations. Prior to that, discussion and collaboration between the NTSB and the VMS staff contributed to the development of the study. The result was a successful simulation and the investigators achieved the objectives of Phase I and Phase II. As noted in the NTSB report of the Phase I activities, it was concluded that the VMS "provided insight and was a beneficial tool for experiencing time synchronized motions, flight control motions, and displays as opposed to just looking at tabular or charted data."[2] The Human Performance Group members also noted that "the VMS was far better in its capability to produce realistic motion cues as compared to a typical hexapod motion-based training simulator."[2]

References

[1]Blakey, M., National Transportation Safety Board Safety Recommendation Letter A-02-01 and -02, URL: http://www.ntsb.gov/events/2001/AA587/ [cited 28 June 2004].

[2]Elias, B., "Human Performance Study Report, Vertical Motion Simulator Activities, Phase I: Backdrive of Accident Flight," National Transportation Safety Board, Office of Aviation Safety, NTSB Number DCA02MA001, Washington, D.C., Oct. 2002.

[3]Brenner, M., "Human Performance Study Report, Vertical Motion Simulator Activities, Phase II Examination," National Transportation Safety Board, Office of Aviation Safety, NTSB Number DCA02MA001, Washington, D.C., Jun. 2003.